Introduction to CHP Technologies

Introduction

Fueled by electric industry deregulation, environmental concerns, unease over energy security, and a host of other factors, interest in combined heat and power (CHP) technologies has been growing among energy customers, regulators, legislators, and developers. CHP is a specific form of distributed generation (DG), which refers to the strategic placement of electric power generating units at or near customer facilities to supply on-site energy needs. CHP enhances the advantages of DG by the simultaneous production of useful thermal and power output, thereby increasing the overall efficiency.

CHP offers energy and environmental benefits over electric-only and thermal-only systems in both central and distributed power generation applications. CHP systems have the potential for a wide range of applications and the higher efficiencies result in lower emissions than separate heat and power generation system. The advantages of CHP broadly include the following:

- The simultaneous production of useful thermal and electrical energy in CHP systems lead to increased fuel efficiency.
- CHP units can be strategically located at the point of energy use. Such onsite generation avoids the transmission and distribution losses associated with electricity purchased via the grid from central stations.
- CHP is versatile and can be coupled with existing and planned technologies for many different applications in the industrial, commercial, and residential sectors.

EPA offers this catalog of CHP technologies as an on-line educational resource for the regulatory, policy, permitting, and other communities. EPA recognizes that some energy projects will not be suitable for CHP; however, EPA hopes that this catalog will assist readers in identifying opportunities for CHP in applications where thermal-only or electric-only generation are currently being considered.

The remainder of this introductory summary is divided into sections. The first section provides a brief overview of how CHP systems work and the key concepts of efficiency and power-to-heat ratios. The second section summarizes the cost and performance characteristics of five CHP technologies in use and under development.

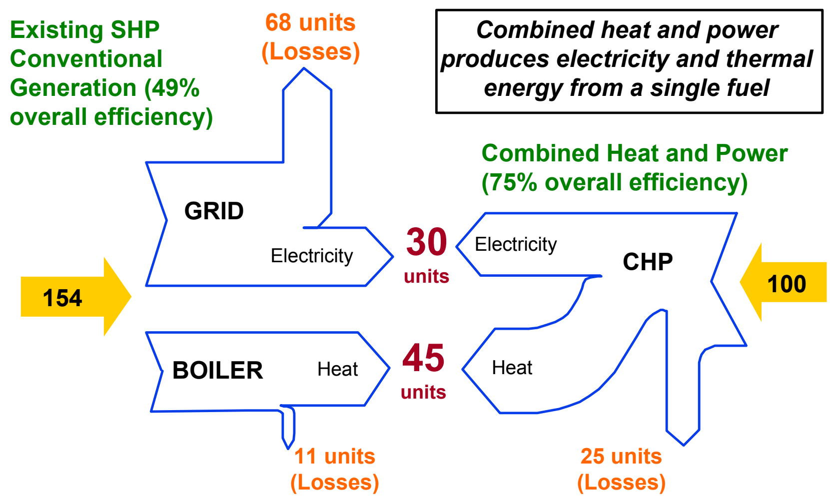
Overview of Combined Heat and Power

What is Combined Heat and Power?

CHP is the sequential or simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) in a single, integrated system. CHP systems consist of a number of individual components – prime mover (heat engine), generator, heat recovery, and electrical interconnection – configured into an integrated whole. The type of equipment that drives the overall system (i.e., the prime mover) typically identifies the CHP system. Prime movers for CHP systems include reciprocating engines, combustion or gas turbines, steam turbines, microturbines, and fuel cells. These prime movers are capable of burning a variety of fuels, including natural gas, coal, oil, and alternative fuels to produce shaft power or mechanical energy. Although mechanical energy from the prime mover is most often used to drive a generator to produce electricity, it can also be used to drive rotating equipment such as compressors, pumps, and fans. Thermal energy from the system can be used in direct process applications or indirectly to produce steam, hot water, hot air for drying, or chilled water for process cooling.

Figure 1 shows the efficiency advantage of CHP compared with conventional central station power generation and on-site boilers. When considering both thermal and electrical processes together, CHP typically requires only ¾ the primary energy separate heat and power systems require. This reduced primary fuel consumption is key to the environmental benefits of CHP, since burning the same fuel more efficiently means fewer emissions for the same level of output.

Figure 1: CHP versus Separate Heat and Power (SHP) Production



Note: Assumes national averages for grid electricity and incorporates electric transmission losses.

Source: Tina Kaarsberg and Joseph Roop, "Combined Heat and Power: How Much Carbon and Energy Can It Save for Manufacturers?"

Expressing CHP Efficiency

Many of the benefits of CHP stem from the relatively high efficiency of CHP systems compared to other systems. Because CHP systems simultaneously produce electricity and useful thermal energy, CHP efficiency is measured and expressed in a number of different ways.[1] Table I summarizes the key elements of efficiency as applied to CHP systems.

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[1] Measures of efficiency are denoted either as lower heating value (LHV) or higher heating value (HHV). HHV includes the heat of condensation of the water vapor in the products. Unless otherwise noted, all efficiency measures in this section are reported on an HHV basis.

Table I: Measuring the Efficiency of CHP Systems

System	Component	Efficiency Measure	Description
Separate heat and power (SHP)	Thermal Efficiency (Boiler)	$EFF_Q = \frac{\text{Net Useful Thermal Output}}{\text{Energy Input}}$	Net useful thermal output for the fuel consumed
	Electric-only generation	$EFF_P = \frac{\text{Power Output}}{\text{Energy Input}}$	Electricity Purchased From Central Stations via Transmission Grid
	Overall Efficiency of separate heat and power (SHP)	$EFF_{SHP} = \frac{P + Q}{P/EFF_{Power} + Q/EFF_{Thermal}}$	Sum of net power (P) and useful thermal energy output (Q) divided by the sum of fuel consumed to produce each.
Combined heat and power (CHP)	Total CHP System Efficiency	$EFF_{Total} = (P + Q)/F$	Sum of the net power and net useful thermal output divided by the total fuel (F) consumed.
	FERC Efficiency Standard	$EFF_{FERC} = \frac{(P + Q/2)}{F}$	Developed for the Public Utilities Regulatory Act of 1978, the FERC methodology attempts to recognize the quality of electrical output relative to thermal output.
	Effective Electrical Efficiency (or Fuel Utilization Efficiency, FUE):	$FUE = \frac{P}{F - Q/EFF_{Thermal}}$	Ratio of net power output to net fuel consumption, where net fuel consumption excludes the portion of fuel used for producing useful heat output. Fuel used to produce useful heat is calculated assuming typical boiler efficiency, usually 80%.
	Percent Fuel Savings	$S = 1 - \frac{F}{P/EFF_P + Q/EFF_Q}$	Fuel savings compares the fuel used by the CHP system to a separate heat and power system. Positive values represent fuel savings while negative values indicate that the CHP system is using more fuel than SHP.

Key:
P = Net power output from CHP system
Q = Net useful thermal energy from CHP system
F = Total fuel input to CHP system
EFF_P = Efficiency of displaced electric generation
EFF_Q = Efficiency of displaced thermal generation

As illustrated in Table I the efficiency of electricity generation in power-only systems is determined by the relationship between net electrical output and the amount of fuel used for the power generation. **Heat rate**, the term often used to express efficiency in such power generation systems, is represented in terms of Btus of fuel consumed per kWh of electricity generated. However, CHP plants produce useable heat as well as electricity. In CHP systems, the **total CHP efficiency** seeks to capture the energy content of both electricity and usable steam and is the net electrical output plus the net useful thermal output of the CHP system divided by the fuel consumed in the production of electricity and steam. While total CHP efficiency provides a measure for capturing the energy content of electricity and steam produced it does not adequately reflect the fact that electricity and steam have different qualities. The quality and value of electrical output is higher relative to heat output and is evidenced by the fact that electricity can be transmitted over long distances and can be converted to other forms of energy. To account for these differences in quality, the Public Utilities Regulatory Policies Act of 1978 (PURPA) discounts half of the thermal energy in its calculation of the efficiency standard (Eff_{FERC}). The EFF_{FERC} is represented as the ratio of net electric output plus half of the net thermal output to the total fuel used in the CHP system. Opinions vary as to whether the standard was arbitrarily set, but the FERC methodology does recognize the value of different forms of energy. The following equation calculates the FERC efficiency value for CHP applications.

$$EFF_{FERC} = \frac{P + Q/2}{F}$$

Where: P = Net power output from CHP system F = Total fuel input to CHP system Q = Net thermal energy from CHP system

Another definition of CHP efficiency is **effective electrical efficiency**, also known as **fuel utilization effectiveness (FUE)**. This measure expresses CHP efficiency as the ratio of net electrical output to net fuel consumption, where net fuel consumption excludes the portion of fuel that goes to producing useful heat output. The fuel used to produce useful heat is calculated assuming typical boiler efficiency, generally 80%. The effective electrical efficiency measure for CHP captures the value of both the electrical and thermal outputs of CHP plants. The following equation calculates FEU.

$$FUE = \frac{P}{F - Q/EFF_Q}$$

Where: Eff_Q = Efficiency of displaced thermal generation

FEU captures the value of both the electrical and thermal outputs of CHP plants and it specifically measures the efficiency of generating power through the incremental fuel consumption of the CHP system.

EPA considers fuel savings as the appropriate term to use when discussing CHP benefits relative to separate heat and power (SHP) operations. Fuel savings compares the fuel used by the CHP system to a separate heat and power system (i.e. boiler and electric-only generation). The following equation determines percent fuel savings (S).

$$S = 1 - \left[\frac{F}{P/Eff_P + Q/Eff_Q} \right]$$

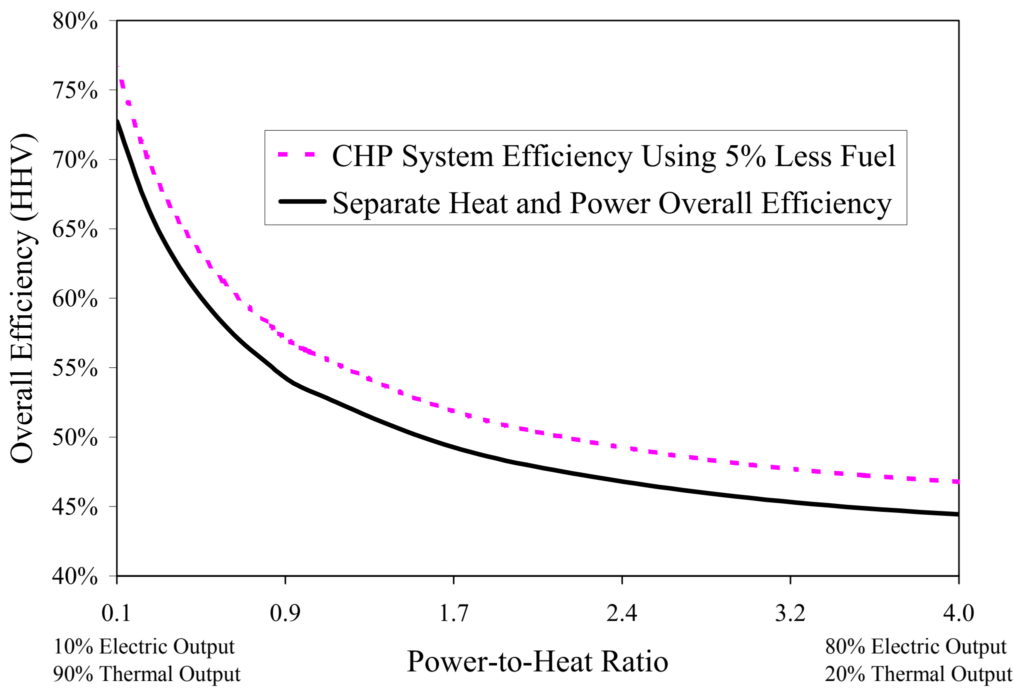
Where: Eff_P = Efficiency of displaced electric generation Eff_Q = Efficiency of displaced thermal-only facility

In the fuel saving equation given above, the numerator in the bracket term denotes the fuel used in the production of electricity and steam in a CHP system. The denominator describes the sum of the fuel used in the production of electricity (P/Eff_P) and thermal energy (Q/Eff_Q) in separate heat-and-power operations. Positive values represent fuel savings while negative values indicate that the CHP system in question is using more fuel than separate heat and power generation.

Another important concept related to CHP efficiency is the **power-to-heat ratio**. The power-to-heat ratio indicates the proportion of power (electrical or mechanical energy) to heat energy (steam or hot water) produced in the CHP system. Because the efficiencies of power generation and steam generation are likely to be considerably different, the power-to-heat ratio has an important bearing on how the total CHP system efficiency of the CHP system might compare to a separate power-and-heat system. Figure 2 illustrates this point. The illustrative curves display how the overall efficiency might change under alternate power-to-heat ratios for a separate power-and-heat system and a CHP system (for illustrative purposes, the CHP system is assumed to use 5% less fuel than its separate heat-and-power counterpart for the same level of electrical and thermal output).

Figure 2: Equivalent Separate Heat and Power Efficiency

Assumes 40% efficient electric and 80% efficient thermal generation



Overview of CHP Technologies

This catalog is comprised of five chapters that characterize each of the different CHP technologies (gas turbine, reciprocating engines, steam turbines, microturbines, and fuel cells) in detail. Many of these technologies are commonly used today, some are in the early stages of commercialization, and others are expected to be available in a few years. The chapters supply information on the applications of the technology, detailed descriptions of its functionality and design characteristics, performance characteristics, emissions, and emissions control options. The following sections provide snapshots of the five technologies, and a comparison of key cost and performance characteristics across the range of technologies that highlights the distinctiveness of each. Tables II and III provide a summary of the key cost and performance characteristics of the CHP technologies discussed in the catalog.

<table>
<tr><th colspan="4">Table II: Summary of CHP Technologies</th></tr>
<tr><th>CHP system</th><th>Advantages</th><th>Disadvantages</th><th>Available sizes</th></tr>
<tr><td>Gas turbine</td><td>High reliability.
Low emissions.
High grade heat available.
No cooling required.</td><td>Require high pressure gas or in-house gas compressor.
Poor efficiency at low loading.
Output falls as ambient temperature rises.</td><td>500 kW to 40 MW</td></tr>
<tr><td>Microturbine</td><td>Small number of moving parts.
Compact size and light weight.
Low emissions.
No cooling required.</td><td>High costs.
Relatively low mechanical efficiency.
Limited to lower temperature cogeneration applications.</td><td>30 kW to 350 kW</td></tr>
<tr><td>Spark ignition (SI) reciprocating engine</td><td rowspan="3">High power efficiency with part-load operational flexibility.
Fast start-up.
Relatively low investment cost.
Can be used in island mode and have good load following capability.
Can be overhauled on site with normal operators.
Operate on low-pressure gas.</td><td rowspan="3">High maintenance costs.
Limited to lower temperature cogeneration applications.
Relatively high air emissions.
Must be cooled even if recovered heat is not used.
High levels of low frequency noise.</td><td>< 5 MW</td></tr>
<tr><td rowspan="2">Diesel/compression ignition (CI) reciprocating engine</td><td>High speed (1,200 RPM) ≤4MW</td></tr>
<tr><td>Low speed (60-275 RPM) ≤65MW</td></tr>
<tr><td>Steam turbine</td><td>High overall efficiency.
Any type of fuel may be used.
Ability to meet more than one site heat grade requirement.
Long working life and high reliability.
Power to heat ratio can be varied.</td><td>Slow start up.
Low power to heat ratio.</td><td>50 kW to 250 MW</td></tr>
<tr><td>Fuel Cells</td><td>Low emissions and low noise.
High efficiency over load range.
Modular design.</td><td>High costs.
Low durability and power density.
Fuels requiring processing unless pure hydrogen is used.</td><td>200 kW to 250 kW</td></tr>
</table>

Table III: Summary Table of Typical Cost and Performance Characteristics by CHP Technology Type*						
Technology	**Steam turbine[1]**	**Diesel engine**	**Nat. gas engine**	**Gas turbine**	**Microturbine**	**Fuel cell**
Power efficiency (HHV)	15-38%	27-45%	22-40%	22-36%	18-27%	30-63%
Overall efficiency (HHV)	80%	70-80%	70-80%	70-75%	65-75%	65-80%
Effective electrical efficiency	75%	70-80%	70-80%	50-70%	50-70%	60-80%
Typical capacity (MW_e)	0.2-800	0.03-5	0.05-5	1-500	0.03-0.35	0.01-2
Typical power to heat ratio	0.1-0.3	0.5-1	0.5-1	0.5-2	0.4-0.7	1-2
Part-load	ok	good	ok	poor	ok	good
CHP Installed costs ($/kW$_e$)	300-900	900-1,500	900-1,500	800-1,800	1,300-2,500	2,700-5,300
O&M costs ($/kWh$_e$)	<0.004	0.005-0.015	0.007-0.02	0.003-0.0096	0.01 (projected)	0.005-0.04
Availability	near 100%	90-95%	92-97%	90-98%	90-98%	>95%
Hours to overhauls	>50,000	25,000-30,000	24,000-60,000	30,000-50,000	5,000-40,000	10,000-40,000
Start-up time	1 hr - 1 day	10 sec	10 sec	10 min - 1 hr	60 sec	3 hrs - 2 days
Fuel pressure (psi)	n/a	<5	1-45	120-500 (compressor)	40-100 (compresor)	0.5-45
Fuels	all	diesel, residual oil	natural gas, biogas, propane, landfill gas	natural gas, biogas, propane, oil	natural gas, biogas, propane, oil	hydrogen, natural gas, propane, methanol
Noise	high	high	high	moderate	moderate	low
Uses for thermal output	LP-HP steam	hot water, LP steam	hot water, LP steam	heat, hot water, LP-HP steam	heat, hot water, LP steam	hot water, LP-HP steam
Power Density (kW/m^2)	>100	35-50	35-50	20-500	5-70	5-20
NO_x[2], lb/MMbtu	0.03-0.3	1-1.8[3]	0.18	0.05	0.03	0.004
lb/MWh$_{TotalOutput}$	0.13-1.3	4.3-8.2[4]	0.8	0.25	0.15	0.02

* Data are illustrative values for 'typically' available systems; All $ are in 2000$

[1] For steam turbine, not entire boiler package

[2] New low emitting units without end of pipe controls

[3] Present on road diesel requirements are approximately 1 lb/MMBtu, but most backup diesel generators emit at 1.8 lb/MMBtu

[4] New on road diesel rule would bring emissions rate to approximately 0.3 lb/MWh$_{TotalOutput}$

Technology

The first chapter of the catalog focuses on gas turbines as a CHP technology. Gas turbines are typically available in sizes ranging from 500 kW to 250 MW and can operate on a variety of fuels such as natural gas, synthetic gas, landfill gas, and fuel oils. Most gas turbines typically operate on gaseous fuel with liquid fuel as a back up. Gas turbines can be used in a variety of configurations including (1) simple cycle operation with a single gas turbine producing power only, (2) combined heat and power (CHP) operation with a single gas turbine coupled and a heat recovery exchanger and (3) combined cycle operation in which high pressure steam is generated from recovered exhaust heat and used to produce additional power using a steam turbine. Some combined cycles systems extract steam at an intermediate pressure for use and are combined cycle CHP systems. Many industrial and institutional facilities have successfully used gas turbines in CHP mode to generate power and thermal energy on-site. Gas turbines are well suited for CHP because their high-temperature exhaust can be used to generate process steam at conditions as high as 1,200 pounds per square inch gauge (psig) and 900 degree Fahrenheit (ºF). Much of the gas turbine-based CHP capacity currently existing in the United States consists of large combined-cycle CHP systems that maximize power production for sale to the grid. Simple-cycle CHP applications are common in smaller installations, typically less than 40 MW.

The second chapter of the catalog focuses on microturbines, which are small electricity generators that can burn a wide variety of fuels including natural gas, sour gases (high sulfur, low Btu content), and liquid fuels such as gasoline, kerosene, and diesel fuel/distillate heating oil. Microturbines use the fuel to create high-speed rotation that turns an electrical generator to produce electricity. In CHP operation, a heat exchanger referred to as the exhaust gas heat exchanger, transfers thermal energy from the microturbine exhaust to a hot water system. Exhaust heat can be used for a number of different applications including potable water heating, absorption chillers and desiccant dehumidification equipment, space heating, process heating, and other building uses. Microturbines entered field-testing in 1997 and the first units began commercial service in 2000. Available and models under development typically range in sizes from 30 kW to 350 kW.

The third chapter in the catalog describes the various types of reciprocating engines used in CHP applications. Spark ignition (SI) and compression ignition (CI) are the most common types of reciprocating engines used in CHP-related projects. SI engines use spark plugs with a high-intensity spark of timed duration to ignite a compressed fuel-air mixture within the cylinder. SI engines are available in sizes up to 5 MW. Natural gas is the preferred fuel in electric generation and CHP applications of SI; however, propane, gasoline and landfill gas can also be used. Diesel engines, also called CI engines, are among the most efficient simple-cycle power generation options in the market. These engines operate on diesel fuel or heavy oil. Dual fuel engines, which are diesel compression ignition engines predominantly fueled by natural gas with a small amount of diesel pilot fuel, are also used. Higher speed diesel engines (1,200 rpm) are available up to 4 MW in size, while lower speed diesel engines (60 - 275 rpm) can be as large as 65 MW. Reciprocating engines start quickly, follow load well, have good part-load efficiencies, and generally have high reliabilities. In many instances, multiple reciprocating engine units can be used to enhance plant capacity and availability. Reciprocating engines are well suited for applications that require hot water or low-pressure steam.

The fourth chapter of the catalog is dedicated to steam turbines that generate electricity from the heat (steam) produced in a boiler. The energy produced in the boiler is transferred to the turbine through high-pressure steam that in turn powers the turbine and generator. This separation of functions enables steam turbines to operate with a variety of fuels including natural gas, solid waste, coal, wood, wood waste, and agricultural by-products. The capacity of commercially available steam turbine typically ranges between 50 kW to over 250 MW. Although steam turbines are competitively priced compared to other prime movers, the costs of a complete boiler/steam turbine CHP system is relatively high on a per kW basis. This is because steam turbines are typically sized with low power to heat (P/H) ratios, and have high capital costs associated with the fuel and steam handling systems and the custom nature of most installations. Thus the ideal applications of steam turbine-based CHP systems include medium- and large-scale industrial or institutional facilities with high thermal loads and where solid or waste fuels are readily available for boiler use.

Chapter five in the catalog deals with an emerging technology that has the potential to serve power and thermal needs cleanly and efficiently. Fuel cells use an electrochemical or battery-like process to convert the chemical energy of hydrogen into water and electricity. In CHP applications, heat is generally recovered in the form of hot water or low-pressure steam (<30 psig) and the quality of heat is dependent on the type of fuel cell and its operating temperature. Fuel cells use hydrogen, which can be obtained from natural gas, coal gas, methanol, and other hydrocarbon fuels. There are currently five types of fuel cells under development. These include (1) phosphoric acid (PAFC), (2) proton exchange membrane (PEMFC), (3) molten carbonate (MCFC), (4) solid oxide (SOFC), and (5) alkaline (AFC). Currently, there are only two commercially available fuel cells, a 200 kW PAFC unit and a 250 kW MCFC unit. Due to the high installed cost of fuel cell systems, the most prominent DG applications of fuel cell systems are CHP-related.

Installed cost[2]

The total plant cost or installed cost for most CHP technologies consists of the total equipment cost plus installation labor and materials, engineering, project management, and financial carrying costs during the construction period. The cost of the basic technology package plus the costs for added systems needed for the particular application comprise the total equipment cost.

Total installed costs for gas turbines, microturbines, reciprocating engines, and steam turbines are comparable. The total installed cost for typical gas turbines ranges from $785/kW to $1,780/kW while total installed costs for typical microturbines in grid-interconnected CHP applications may range anywhere from $1,339/kW to $2,516/kW. Commercially available natural gas spark-ignited engine gensets have total installed costs of $920/kW to $1,515/kW, and steam turbines have total installed costs ranging from $349/kW to $918/kW. Fuel cells are currently the most expensive among the five CHP technologies with total installed costs ranging between $4,500/kW (for a 200 PAFC unit) to $5,000/kW (for a 250 MCFC unit).

O&M Cost

Non-fuel operation and maintenance (O&M) costs typically include routine inspections, scheduled overhauls, preventive maintenance, and operating labor. O&M costs are comparable for gas turbines, gas engine gensets, steam turbines and fuel cells, and only a fraction higher for microturbines. Total O&M costs range from $4.2/MWh to $9.6/MWh for typical gas turbines, from $9.3/MWh to $18.4/MWh for commercially available gas engine gensets and are typically

[2] All $ are 2000$.

less than $4/MWh for steam turbines. Based on manufacturers offer service contracts for specialized maintenance, the O&M costs for microturbines appear to be around $10/MWh. For fuel cells O&M costs range approximately between $29/MW and $43/MW.

Start-up time

Start-up times for the five CHP technologies described in this catalog can vary significantly depending on the technology and fuel used. Gas turbines have relatively short start up time, though heat recovery considerations may constraint start up times. Microturbines require several minutes for start-up but requires a power storage unit (typically a battery UPS) for start-up if the microturbine system is operating independent of the grid. Reciprocating engines have fast start-up capability, which allows for timely resumption of the system following a maintenance procedure. In peaking or emergency power applications, reciprocating engines can most quickly supply electricity on demand. Steam turbines, on the other hand, require long warm-up periods in order to obtain reliable service and prevent excessive thermal expansion, stress and wear. Fuel cells also have relatively long start-up times (especially for MCFC and SOFC). The longer start-up times for steam turbines and fuel cells make it more applicable to baseload needs.

Availability

Availability indicates the amount of time a unit can be used for electricity and/or steam production. Availability generally depends on the operational conditions of the unit. Frequent starts and stops of gas turbines can increase the likelihood of mechanical failure, though steady operation with clean fuels can permit gas turbines to operate for about a year without a shutdown. The estimated availability for gas turbines operating on clean gaseous fuels such as natural gas is over 95 percent.

Given the limited number of microturbines currently in commercial use it is difficult to draw conclusions on the reliability and availability of these units. At the same time, the basic design and limited number of moving parts in microturbines suggests that the technology will have good availability. Manufacturers of microturbines have targeted availabilities between 98 and 99 percent. Natural gas engine availabilities generally vary with engine type, speed, and fuel quality. Typically demonstrated availabilities for natural gas engine gensets in CHP applications is approximately 95 percent. Steam turbines have high availability rates -- usually greater than 99 percent with longer than one year between shutdowns for maintenance and inspections. However, for purposes of CHP application it should be noted that this high availability rate is only applicable to the steam turbine itself and not to the boiler or HRSG that is supplying the steam. Some demonstrated and commercially available fuel cells have achieved greater than 90 percent availability.

Thermal output

The ability to produce useful thermal energy from exhaust gases is the primary advantage of CHP technologies. Gas turbines produce a high quality (high temperature) thermal output suitable for most CHP applications. High-pressure steam can be generated or the exhaust can be used directly for process heating and drying. Microturbines produce exhaust output at temperatures in the 400ºF - 600ºF range, suitable for supplying a variety of building thermal needs. Reciprocating engines can produce hot water and low-pressure steam. Steam turbines are capable of operating over a broad range of steam pressures. They are custom designed to deliver the thermal requirements of CHP applications through use of backpressure or extraction steam at the appropriately needed pressure and temperature. Waste heat from fuel cells can be used primarily for domestic hot water and space heating applications.

Efficiency

Total CHP efficiency is a composite measure of the CHP fuel conversion capability and is expressed as the ratio of net output to fuel consumed. As explained earlier, for any technology the total CHP efficiency will vary depending on size and power-to-heat ratio. Combustion turbines achieve higher efficiencies at greater size and with higher power-to-heat ratios. The total CHP efficiency for gas turbines between 1 MW and 40 MW range from 70 percent to 75 percent for power-to-heat ratio between 0.5 to 1.0 respectively. Unlike gas turbines, microturbines typically achieve 65 percent to 75 percent total CHP efficiency for a range of power-to-heat ratios. Commercially available natural gas spark engines ranging between 100 kW to 5 MW are likely to have total CHP efficiency in the 75 percent to 80 percent. The total CHP efficiency of such engines will decrease with unit-size, and also with higher power-to-heat ratios. Although performance of steam turbines may differ substantially based on the fuel used, they are likely to achieve near 80 percent total CHP efficiency across a range of sizes and power-to–heat ratios. Fuel cell technologies may achieve total CHP efficiency in the 65 percent to 75 percent range.

Emissions

In addition to cost savings, CHP technologies offer significantly lower emissions rates compared to separate heat and power systems. The primary pollutants from gas turbines are oxides of nitrogen (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) (unburned, non-methane hydrocarbons). Other pollutants such as oxides of sulfur (SO_x) and particulate matter (PM) are primarily dependent on the fuel used. Similarly emissions of carbon dioxide are also dependent on the fuel used. Many gas turbines burning gaseous fuels (mainly natural gas) feature lean premixed burners (also called dry low-NO_x burners) that produce NO_x emissions ranging between 0.3 lbs/MWh to 2.5 lbs/MWh with no post combustion emissions control. Typically commercially available gas turbines have CO emissions rates ranging between 0.4 lbs/MWh – 0.9 lbs/MWh. Selective catalytic reduction (SCR) or catalytic combustion can further help to reduce NO_x emissions by 80 percent to 90 percent from the gas turbine exhaust and carbon-monoxide oxidation catalysts can help to reduce CO by approximately 90 percent. Many gas turbines sited in locales with stringent emission regulations use SCR after-treatment to achieve extremely low NO_x emissions.

Microturbines have the potential for low emissions. All microturbines operating on gaseous fuels feature lean premixed (dry low NO_x, or DLN) combustor technology. The primary pollutants from microturbines include NO_x, CO, and unburned hydrocarbons. They also produce a negligible amount of SO_2. Microturbines are designed to achieve low emissions at full load and emissions are often higher when operating at part load. Typical NO_x emissions for microturbine systems range between 0.5 lbs/MWh and 0.8 lbs/MWh. Additional NO_x emissions removal from catalytic combustion is microturbines is unlikely to be pursued in the near term because of the dry low NO_x technology and the low turbine inlet temperature. CO emissions rates for microturbines typically range between 0.3 lbs/MWh and 1.5 lbs/MWh.

Exhaust emissions are the primary environmental concern with reciprocating engines. The primary pollutants from reciprocating engines are NO_x, CO, and VOCs. Other pollutants such as SO_x and PM are primarily dependent on the fuel used. The sulfur content of the fuel determines emissions of sulfur compounds, primarily SO_2. NO_x emissions from reciprocating engines typically range between 1.5 lbs/MWh to 44 lbs/MWh without any exhaust treatment.

Use of an oxidation catalyst or a three way conversion process (non-selective catalytic reductions) could help to lower the emissions of NO_x, CO and VOCs by 80 percent to 90 percent. Lean burn engines also achieve lower emissions rates than rich burn engines.

Emissions from steam turbines depend on the fuel used in the boiler or other steam sources, boiler furnace combustion section design, operation, and exhaust cleanup systems. Boiler emissions include NO_x, SO_x, PM, and CO. The emissions rates in steam turbine depend largely on the type of fuel used in the boiler. Typical boiler emissions rates for NO_x with any post-combustion treatment range between 0.2 lbs/MWh and 1.24 lbs/MMBtu for coal, 0.22 lbs/MMBtu to 0.49 lbs/MMBtu for wood, 0.15 lbs/MMBtu to 0.37 lbs/MMBtu for fuel oil, and 0.03lbs/MMBtu – 0.28 lbs/MMBtu for natural gas. Uncontrolled CO emissions rates range between 0.02 lbs/MMBtu to 0.7 lbs/MMBtu for coal, approximately 0.06 lbs/MMBtu for wood, 0.03 lbs/MMBtu for fuel oil and 0.08 lbs/MMBtu for natural gas. A variety of commercially available combustion and post-combustion NO_x reduction techniques exist with selective catalytic reductions achieving reductions as high as 90 percent.

SO_2 emissions from steam turbine depend largely on the sulfur content of the fuel used in the combustion process. SO_2 composes about 95% of the emitted sulfur and the remaining 5 percent are emitted as sulfur tri-oxide (SO_3). Flue gas desulphurization (FGD) is the most commonly used post-combustion SO_2 removal technology and is applicable to a broad range of different uses. FGD can provide up to 95 percent SO_2 removal.

Fuel cell systems have low emissions profiles because the primary power generation process does not involve combustion. The fuel processing subsystem is the only significant source of emissions as it converts fuel into hydrogen and low energy hydrogen exhaust stream. The hydrogen exhaust stream is combusted in the fuel processor to provide heat, achieving emissions signatures of less than 0.07 lbs/MWh of CO, less than 0.06 lbs/MWh of NO_x and negligible SO_x without any after-treatment for emissions. Fuel cells are not expected to require any emissions control devices to meet current and projected regulations.

While not considered a pollutant in the ordinary sense of directly affecting health, CO_2 emissions do result from the use the fossil fuel based CHP technologies. The amount of CO2 emitted in any of the CHP technologies discussed above depends on the fuel carbon content and the system efficiency. The fuel carbon content of natural gas is 34 lbs carbon/MMBtu; oil is 48 lbs of carbon/MMBtu and ash-free coal is 66 lbs of carbon/MMBtu.

Appendix 1: Fuel Savings Equations

Absolute Fuel Savings:

$$F_{CHP} = F_{SHP} * (1 - S) \text{ and } E_{SHP} = E_{CHP} * (1 - S)$$

$$\text{Fuel Savings} = F_{SHP} - F_{CHP} = \frac{F_{CHP}}{1 - S} - F_{CHP}$$

Where F_{CHP} = CHP fuel use
F_{SHP} = SHP fuel use
S = % fuel savings compared to SHP
E_{CHP} = CHP efficiency
E_{SHP} = SHP efficiency

$$= F_{CHP}\left[\frac{1}{1-S} - 1\right] = F_{CHP}\left[\frac{1}{1-S} - \frac{1-S}{1-S}\right] = F_{CHP}\left[\frac{1-1+S}{1-S}\right]$$

$$\text{Fuel Savings} = F_{CHP}\left[\frac{S}{1-S}\right] = F_{SHP} - F_{SHP} * (1 - S) = F_{SHP} * S$$

Percentage Fuel Savings:

Equivalent separate heat and power (SHP) efficiency

$$Eff_{SHP} = \frac{\text{SHP Output}}{\text{SHP Fuel Input}} = \frac{P + Q}{P/Eff_P + Q/Eff_Q}$$

Where P = power output
Q = useful thermal output
Eff_P = power generation efficiency
Eff_Q = thermal generation efficiency

divide numerator and denominator by (P+Q)

$$Eff_{SHP} = \frac{1}{\frac{\%P}{Eff_P} + \frac{\%Q}{Eff_Q}}$$

Where %P = P/(P+Q)
%Q = Q/(P+Q)

CHP efficiency

$$Eff_{CHP} = \frac{P + Q}{F_{CHP}} = \frac{Eff_{SHP}}{(1 - S)}$$

Substitute in equation for EFF_{SHP} and isolate S

$$\frac{P + Q}{F} = \frac{\frac{P + Q}{P/EFF_P + Q/EFF_Q}}{(1 - S)}$$

$$(1-S)*\frac{P+Q}{F}=\frac{P+Q}{P/EFF_P+Q/EFF_Q}$$

Divide out (P+Q) and multiply by F

$$1-S=\frac{F}{\left(\frac{P}{Eff_P}+\frac{Q}{Eff_Q}\right)}$$

Percent fuel savings calculated from power and thermal output, CHP fuel input, and efficiency of displaced separate heat and power.

$$\boxed{S=1-\frac{F}{\frac{P}{Eff_P}+\frac{Q}{Eff_Q}}}$$

<u>Calculation of percentage power or percent thermal output from power to heat ratio:</u>

$$\text{Power to Heat Ratio}=X=P/Q=\%P/\%Q$$

$$P+Q=1$$

$P=X*Q$	$Q=\frac{P}{X}$
$P=X*(1-P)$	$Q=\frac{1-Q}{X}$
$P=X-X*P$	
$P+X*P=X$	$Q*X=1-Q$
$P*(1+X)=X$	$Q*(X+1)=1$
$P=\frac{X}{1+X}$	$Q=\frac{1}{X+1}$